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Euler and Navier-Stokes Simulations of Shock Wave Interaction With a Generic Block Target

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13. ABSTRACT *(Maximum 200 words)*

A series of numerical simulations of blast wave/target interaction was performed to match a series of experiments conducted at the Centre d'Etudes de Gramat (CEG), France. The experiments that were modeled involved a square, two-dimensional block target positioned in the vertical center of a shock tube test section and subjected to non-decaying blast waves of various amplitudes. The results of the inviscid second order hydrodynamic advanced research code (SHARC) and the viscous USA-RG2 code simulations are compared to experimentally measured pressure histories. Particular emphasis is placed on the accurate modeling of vortex formation and evolution, which influences the aerodynamic loading of the target. The viscous and inviscid results are directly compared to determine the most accurate method of modeling both diffraction and drag phase blast loading of targets.

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Mr. Richard J. Pearson performed a technical review of this report and provided many useful comments to clarify and improve the presentation of the work that is described.

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1. Introduction

To study the phenomenology of nuclear blast loading on military equipment, laboratory shock tubes are sometimes configured to produce simulations of nuclear blast waves. The laboratory environment can provide pressure measurements on surfaces of bodies as well as a means of characterizing the flow field through optical techniques. One laboratory shock tube facility, called Zephire, is located at the Centre d'Etudes de Gramat (CEG), France. The limitation of this laboratory facility is that only simplified, subscale targets can be studied in its environment. To provide a more complete representation of the phenomena, numerical simulation techniques are sometimes employed. These techniques allow more detailed data (density, velocity, dynamic pressure) to be collected in critical areas of interest.

In addition to supplementing experimental data, numerical simulations of blast wave-target interaction can be used to directly model the effects of nuclear blast on tactical equipment. With the rising cost of full scale experimentation and the increasing performance of supercomputers, coupled numerical simulation of blast loading and rigid body response may become an economical method of determining the vulnerability of equipment to nuclear blast effects.

To predict the response of targets to nuclear blast loading, one must first accurately model the aerodynamic loads applied to the targets. Controlled laboratory experiments, such as those performed in the Zephire facility, provide an excellent means of validating the presently employed computational fluid dynamics (CFD) algorithms. This method of validation will also ensure that the most appropriate algorithm is used in high-resolution, three-dimensional (3-D) calculations of blast loading on complex, moving bodies.

2. Shock Tube Facility

The Zephire shock tube facility is operated by CEG for the purpose of studying shock waves and their interactions with targets.[1] The facility can also be used to develop and test measuring equipment and to study possible modifications of larger blast simulation facilities.

The Zephire shock tube is composed primarily of 0.5 m diameter tube sections, each of which is 1 m long. The total maximum length of the shock tube is 45 m. As many as 10 tube sections, each of which is 1 m in length, may be used to construct the driver section for a given experiment. The actual number of tube sections used to construct the driver depends on the desired blast wave characteristics. The expansion section of this facility is also composed of these 0.5 m diameter tube sections and can be a maximum of 35 m long. The driver and expansion sections are separated by a thin diaphragm, which is ruptured with heating wires.

Within the expansion section a test section exists for studying the interactions of shock waves with targets. The center of the test section is located at a position 15 m downstream from the diaphragm. A schematic diagram of the test section positioned within the expansion section is illustrated in Figure 1. The test section is rectangular and has a knife-edged leading

surface that allows the shock wave to enter the test section with minimum disturbance. As illustrated in the figure, the test section has a height of 323 mm, a width of 282 mm, and a total length of 3300 mm between the upstream and downstream knife edges.

Zephire is an excellent facility for studying shock wave-target interactions because it is equipped with high-speed cameras for visualizing the flow during the diffraction and drag phases. Combining these optical data with pressure histories measured on the faces of the target provides detailed information about the evolution of the flow field in the vicinity of the target. In the experiments discussed here, the target employed was a 70 mm by 70 mm block positioned near the vertical center of the test section. This target is also illustrated in Figure 1. Mounted within the target were three pressure gauges that were used to measure pressure histories on the faces of the target. One gauge was mounted in the center of the front face. Another was positioned in the center of the rear face. The third gauge was mounted in the top face of the target, centered at a distance of 31 mm from the upstream edge of the target.

The numerical simulations presented in this paper correspond to three experiments performed in Zephire. These experiments involved the interaction of the block target with non-decaying blast waves of various incident static overpressure amplitudes. The conditions of each experiment are described in Table 1.

Table 1. Conditions of Experiments

	Shot Number		
	1	2	3
Atmospheric Conditions			
Temperature (K)	294.5	294.1	295.8
Pressure (kPa)	97.8	97.3	96.9
Density (kg/m^3)	1.157	1.153	1.141
Shock Properties			
Shock Velocity (m/s)	400.8	434.9	469.6
Shock Mach Number	1.165	1.265	1.362
Conditions Behind Shock			
Static Overpressure (kPa)	40.5	67.8	96.3
Temperature (K)	325.6	343.5	363.7
Density (kg/m^3)	1.479	1.673	1.849
Particle Velocity (m/s)	87.4	135.3	179.7

These experiments were modeled in a series of calculations performed with the second order, hydrodynamic, advanced research code (SHARC) and the universal solution algorithms, real gas, 2-D (USA-RG2) code. A description of each code is provided, followed by a discussion of the results obtained from the numerical simulations.

3. Description of Flow Solvers

Two different computational fluid dynamics codes were used to model the Zephire experiments. The first was SHARC, an explicit Euler solver[2] and is a derivative of the HULL code which was originally developed at the U.S. Air Force Weapons Laboratory for the purpose of modeling nuclear blast loading on missile silos.[3]

SHARC is a finite difference code that employs a rectangular discretized mesh to model the computational domain. The code supports 2-D axisymmetric, 2-D cartesian and 3-D cartesian geometries. Variable spacing of grid points along each coordinate axis is allowed. Complex shapes are modeled by placing a perfectly rigid, perfectly reflective material, known as "island" material, in the rectangular (2-D) or box shaped (3-D) computational cells. The degree to which computational results match experimental results is affected by the grid resolution used. In general, higher grid resolutions lead to better agreement. Increasing grid resolution, however, can quickly lead to unreasonably long run times. The grid resolution selected for a computational study involves a trade off between the accuracy of the result and CPU time.

Early versions of SHARC employed a solution algorithm that was first order accurate in space and time. Later, a second order accurate solution algorithm was added to reduce the diffusiveness of the solution. Another improvement to the SHARC code was the addition of a $k - \epsilon$ turbulence model, which improves the capability of the code in cases that involve shear flow.[4] An artificial viscosity model is also available in the SHARC code. This model can be used as a damping mechanism to minimize the effects of "overshoots" near shock fronts. Even with the artificial viscosity model, SHARC is still an inviscid code. That is, the algorithm in SHARC is a discretization of the Euler equations, a subset of the Navier-Stokes equations, which contain no viscous terms. Thus, SHARC is not capable of modeling the effects of boundary layers. Calculations of the shock-target interactions in the Zephire experiments were performed by SHARC using a variety of solver options and grid configurations. After the SHARC calculations were complete, a second set of computations was performed using Rockwell Science Center's USA-RG2 code.

The USA-RG2 code discretizes the Navier-Stokes equations using a finite volume, Roe's Riemann solver, total variation diminishing (TVD), implicit algorithm.[5] The implicit scheme produces an algorithm that is well suited for blast wave calculations[6] because upwind flux difference splitting with TVD achieves second order accuracy without introducing spurious oscillations near discontinuities. Strong gradients and complex flow fields are resolved accurately. TVD schemes are often referred to as modern shock-capturing methods because the numerical dissipation terms are nonlinear. That is, the amount of dissipation is controlled by automatic feedback mechanisms that can vary from one grid point to another. Also, the dissipation is scaled to the underlying eigensystem of the hyperbolic Euler equations. In classical shock capturing methods, the numerical dissipation terms are either linear so that the same amount of numerical dissipation is added at all grid points or the numerical dissipation is controlled by parameters that must be optimized. Classical shock capturing methods typically result in oscillatory solutions at strong discontinuities.

The conservative nature of the scheme captures shocks and other discontinuities automatically. The finite volume philosophy ensures conservation at interior grid points. The implicit version of the scheme requires more computations per integration step than the explicit version but permits larger time steps which, for mathematically stiff (viscous) problems, reduces computational expense. The code has the capability to handle multi-zone grids and has several turbulence models available. The turbulence models available are a modified Baldwin-Lomax[7] (0 equation), $k - L$[8] (1 equation), and $k - \epsilon$[9] (2 equation) models.

The USA-RG2 code and other computational fluid dynamics codes like it employ gridding techniques that are quite different from those of SHARC. In particular, the coordinate axes are not required to be straight lines. Rather, the coordinate axes can be defined in practically any form necessary to define the complex shape of the system being modeled. This type of grid is referred to as "body conformal" because the grid can be wrapped around the body of interest, thus modeling it with a high level of accuracy. An additional level of flexibility is available to the USA-RG2 code in that it supports multi-zone grids. This basically means that numerous independent body conformal grids can be combined in one computational model to represent the system with a high degree of fidelity without placing a large number of grid points in regions of uniform steady flows.

4. Experimental and Computational Results

The experiments that were performed in the Zephire shock tube were originally followed by a set of hydrocode calculations performed at CEG with an early version of the SHARC code. This version lacked some of the features that were described earlier. Most significantly, this early version of SHARC did not have the second-order accurate solution algorithm and the $k - \epsilon$ turbulence model.

These calculations were 2-D numerical simulations of the flow inside the test section of the Zephire shock tube. Thus, only the rectangular cross section, from the upstream knife edge of the test section to the downstream knife edge, was modeled. It was not necessary to model the circular cross section of the expansion section because the influence of flow disturbances originating from this part of the facility would not reach the target during the period of interest of the experiment. Because the target was positioned near the vertical center of the test section, only half of the flow field was modeled vertically, from the centerline of the target to the upper wall of the test section.

The calculations performed by CEG with this early version of SHARC employed a 522x294 grid and accurately reproduced the experimentally measured pressure histories for the 40.5 kPa and 67.8 kPa incident static overpressure experiments, as illustrated in Figures 2 through 7.

For the 96.8 kPa experiment, the front and rear surface pressure histories produced by SHARC were also a good match to the experimental data, as illustrated in Figures 8 and 9. However, Figure 10 shows that for the top face pressure history, there were significant differences between the experiment and the result of the early SHARC code.

Close examination of Figure 10 explains much about phenomena involved in the shock wave-target interaction. The initial interaction of the shock with the target causes the initial rise in the pressure history, which is followed by a plateau. Behind the primary shock, a vortex is formed at the leading edge of the target and travels downstream across the top face of the target. As this vortex passes over the pressure gauge, the pressure at the gauge begins to decrease. The amount of pressure decrease is a function of the amplitude of the primary shock. A stronger incident shock will generate a lower pressure within this vortex, and thus a greater pressure drop after the initial plateau in the top surface pressure history. This pressure drop, which is combined with a decrease due to a rarefaction wave from the downstream edge, is followed by two sharp increases. These pressure increases are caused by reflections from the top wall of the test section. It is here that the significant differences between the experiment and the calculation occur.

In an attempt to better understand the differences between the top face experimental and computational data for the 96.3 kPa incident static overpressure experiment, ARL performed a series of calculations with its version of the SHARC code. The ARL installation of SHARC contains all the features described earlier in this report. The first calculation employed the exact problem definition as the calculations performed by CEG. The only difference between this calculation and the CEG calculation was that the second order accurate solution algorithm was employed whereas the first order accurate scheme had been used in the CEG calculations. The top surface pressure history result for this calculation can be seen in Figure 11. The second order code results significantly deviate from the experiment starting at about 0.6 ms. Comparing this to Figure 10, one can see that after 0.6 ms, the deviation from the experimental pressure is larger than the first order result.

The second order SHARC calculations performed with the original CEG problem definition resolved the computational domain into a grid containing 522 points in the horizontal direction and 294 points in the vertical direction. As discussed earlier, the spacing between grid points may be varied in this type of finite difference calculation. This particular grid employed a constant grid point spacing of 0.25 mm in both the horizontal and vertical directions in the region close to the target and near the top wall of the test section. Between the top face of the target and the top wall of the test section, the grid point spacing was allowed to grow to a maximum of 2.6 mm. This increase in grid spacing was done in a effort to reduce the time required for the calculation to run. However, it was felt that some of the definition of the complex shock structure between the top face of the target and the top wall of the test section could be artificially dissipated in this region of coarse grid resolution. Consequently, another second order SHARC calculation was performed, which employed a grid with the same 522 grid points in the horizontal direction as the previous calculation, but with 652 grid points in the vertical direction. This new grid used a constant grid spacing of 0.25 mm for the entire vertical distance between the target centerline and the top wall of the test section. The top face pressure history for this calculation is compared to the experimental data in Figure 12. The result is basically the same as that of the 522x294 grid calculation, except that there is more activity near the end of the record.

Because the result of the 522x652 grid calculation showed no significant improvement over the 522x294 grid case, it was decided that the next logical means of refining the grid was to further decrease the size of the cells throughout the computational domain. A final SHARC calculation was performed in which a 958x1072 grid was employed. This calculation used grid point spacing of 0.10 mm near the target in the horizontal and vertical directions. The grid point spacing in the 958x1072 grid was allowed to grow to only 0.20 mm between the top face of the target and the top wall of the test section. The result of this calculation is illustrated in Figure 13. Comparing this figure to the previous SHARC results shows that the 958x1072 grid calculation provided the closest agreement to the experimental data. The 958x1072 grid SHARC calculation required nearly 100 CPU hours to complete on a single processor of a Cray XMP. SHARC calculations with further grid refinement than this were simply not possible due to the long run times which would be required. Therefore, this result is considered to be the best inviscid solution obtainable with the present class of vector supercomputers.

A final set of calculations using the USA-RG2 code was executed on a Cray 2 supercomputer. These calculations employed a 528x848 grid point, five zone grid in which the grid point spacing was 0.1 mm near the surface of the target in both horizontal and vertical directions, identical to the grid resolution near the target in the most highly resolved SHARC calculation. The first USA-RG2 calculation employed a laminar viscous solution scheme, thus assuming that the flow is viscous but nonturbulent and required 2.2 hours of CPU time to complete. The front and rear surface pressure histories for this calculation are compared to the experimental data in Figures 14 and 15, respectively. As with the SHARC results, the USA-RG2 code accurately predicts the flow histories on these surfaces.

The pressure history on the top surface of the target produced by the laminar viscous solution is presented in Figure 16. This figure shows that, until 0.5 milliseconds, the result closely follows the experimental pressure history for the top face of the target, after which, deviations from the experimental data exist.

Three additional USA-RG2 calculations were performed to model the influence of turbulence within the boundary layer. These calculations employed three different turbulence models that are available with the USA-RG2 code: Baldwin-Lomax, $k - L$, and $k - \epsilon$. The results of the calculations with these turbulence models are presented in Figures 17, 18, and 19. The result obtained from the calculation using the Baldwin-Lomax turbulence model, Figure 17, did not predict the pressure history as well as the laminar viscous calculation. The Baldwin-Lomax ran in 2.5 hours, and its result fell well below the minimum pressure following the decay caused by the vortex migration across the top surface.

Figure 18 shows that the calculation that employed the $k-L$ turbulence model accurately predicted the value of the minimum pressure, but following this minimum, the pressure history experienced a rapid increase. When compared to the experimental data, it appears that the reflections from the top wall of the test section arrive too soon in this calculation. This calculation was completed in 5 hours. Finally, the 17.3 hour calculation with the $k - \epsilon$ turbulence model is shown in Figure 19. The top face pressure history from this calculation closely follows the experimental data through the initial shock, the decay, and the minimum

before the first reflection from the top wall of the test section. Both the $k - L$ calculation and the $k - \epsilon$ calculation are improvements over the laminar viscous and Baldwin-Lomax turbulence calculations.

5. Summary

Experiments were conducted in the CEG Zephire shock tube facility to study the interaction of blast waves with a square, 2-D target. Calculations have been performed with an inviscid Euler solver, SHARC, and a full Navier-Stokes code, USA-RG2, to compare to these experiments. Particular emphasis has been placed on the ability of these codes to model the vortex formation and evolution processes that have a significant impact on the aerodynamic loading of surfaces that are parallel to the primary direction of flow. Validation of the computational results was accomplished through the comparison of experimentally measured pressure histories to those obtained from the numerical simulations. The use of a highly resolved grid, combined with a second order accurate solution algorithm, helped to bring the inviscid code result into better agreement with the experiment. However, the inviscid code was still unable to accurately model the flow along the top surface of the target during the drag phase. The four viscous solutions that were presented provided a better correlation to the experimental data, particularly in late time. Of these, the solutions that employed $k - L$ and $k - \epsilon$ turbulence models provided the most accurate simulation of the aerodynamic loading on the top surface of the target. These findings provide a valid argument for the inclusion of turbulent, viscous flow modeling in future 3-D numerical simulations of blast loading on military equipment.

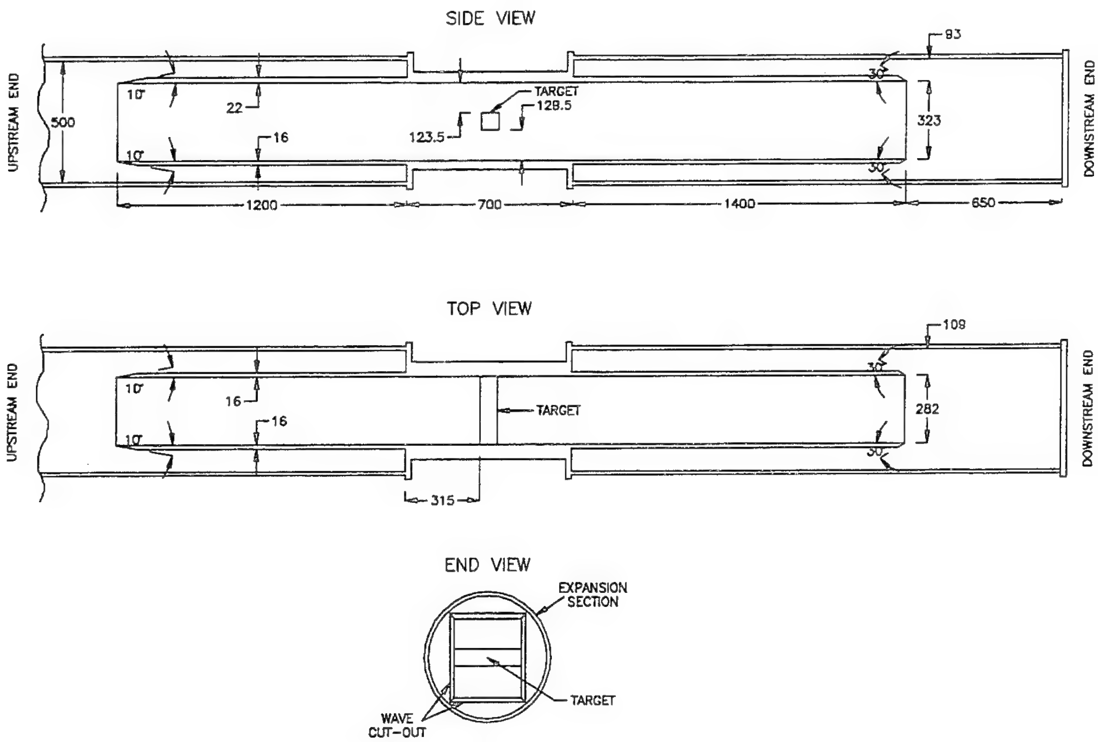

Figure 1. Schematic Diagram of Zephire Test Section

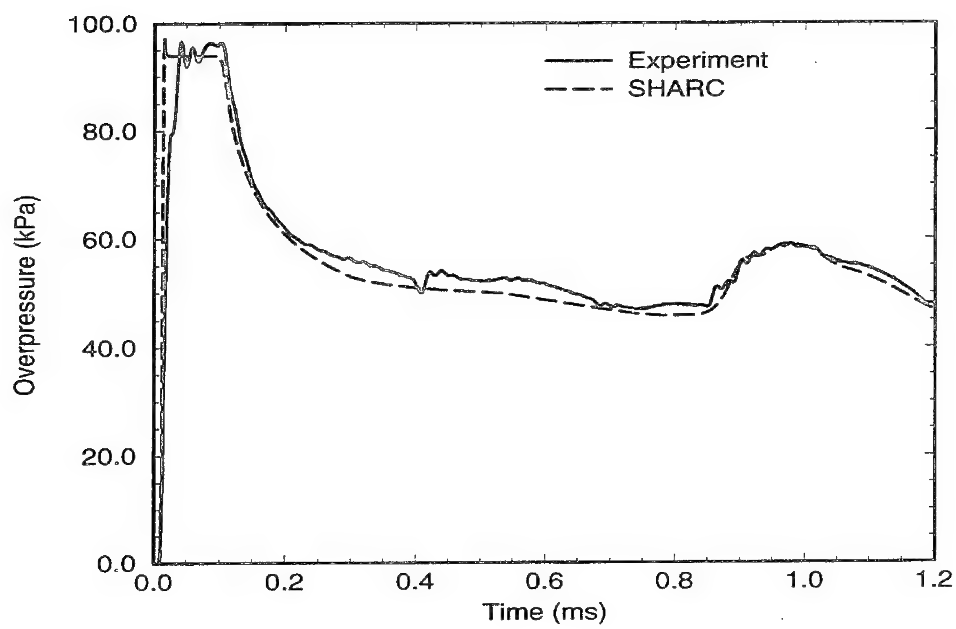

Figure 2. $M_s = 1.165$, Front Face, SHARC: First Order, 522x294 Grid

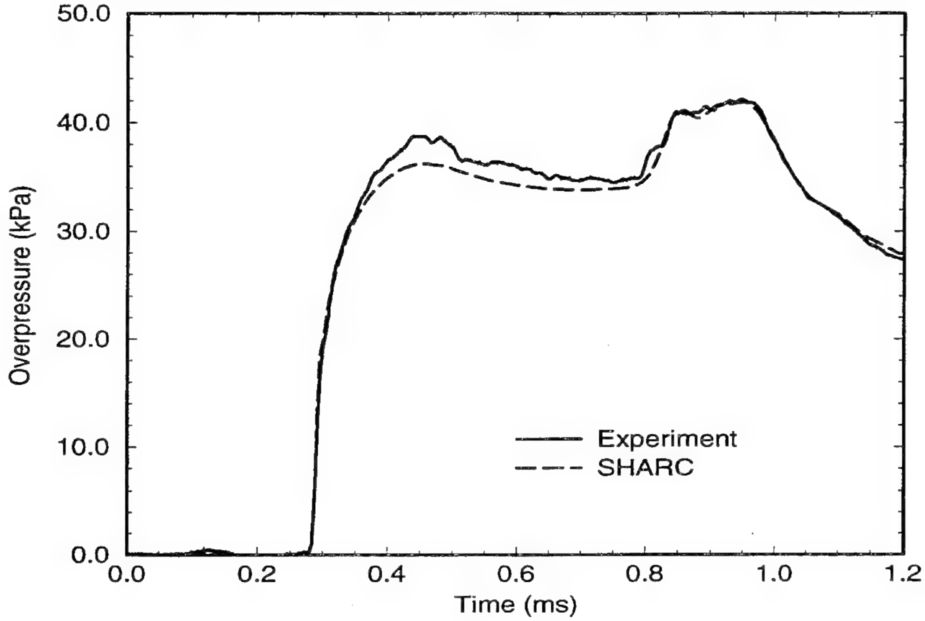

Figure 3. $M_s = 1.165$, Rear Face, SHARC: First Order, 522x294 Grid

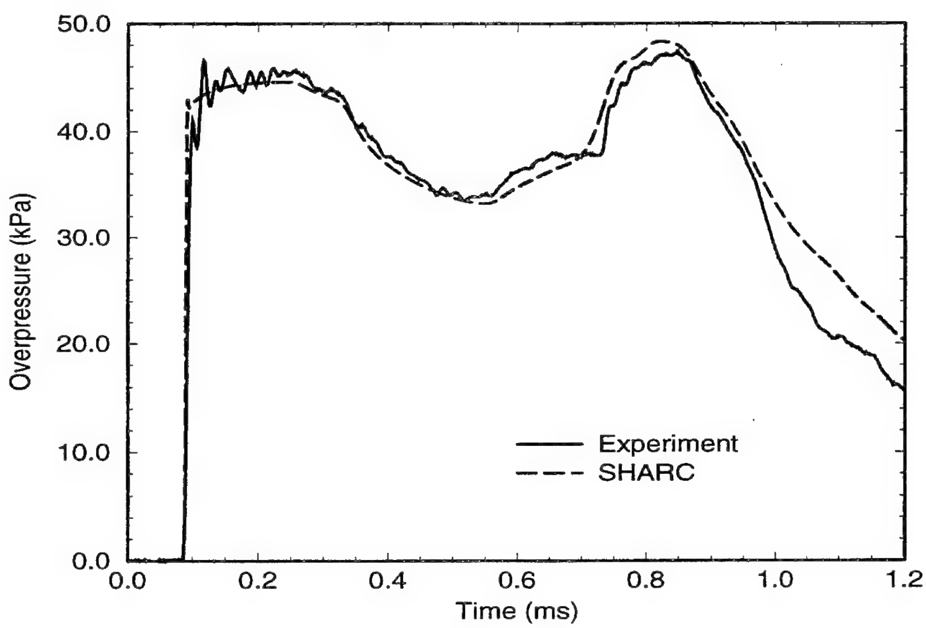

Figure 4. $M_s = 1.165$, Top Face, SHARC: First Order, 522x294 Grid

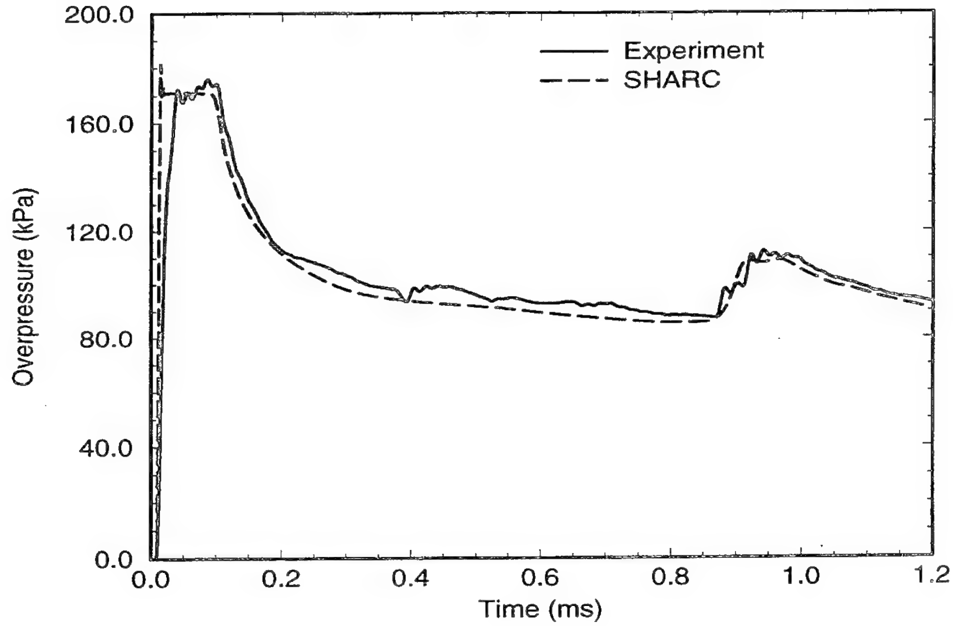

Figure 5. $M_s = 1.265$, Front Face, SHARC: First Order, 522x294 Grid

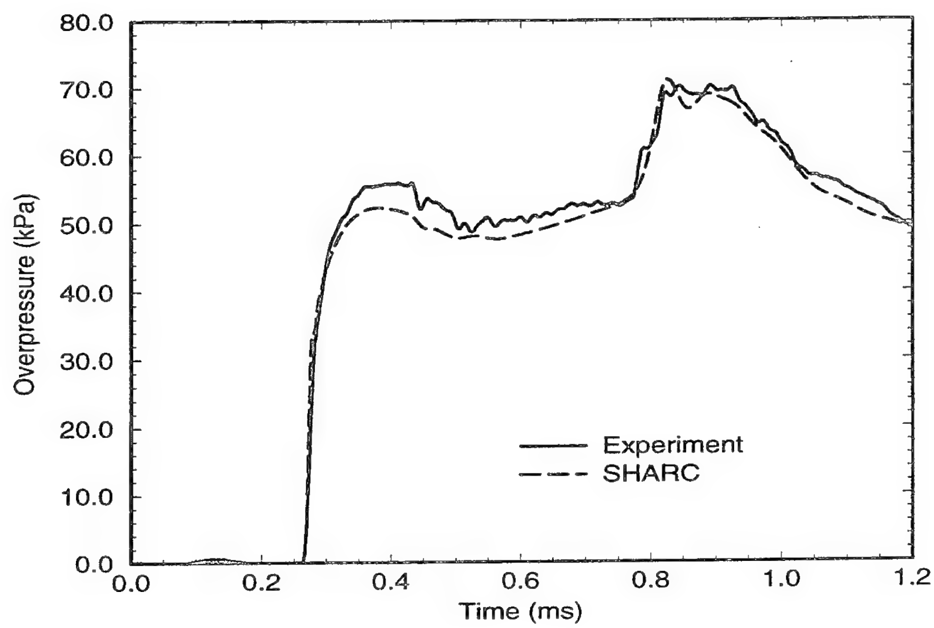

Figure 6. $M_s = 1.265$, Rear Face, SHARC: First Order, 522x294 Grid

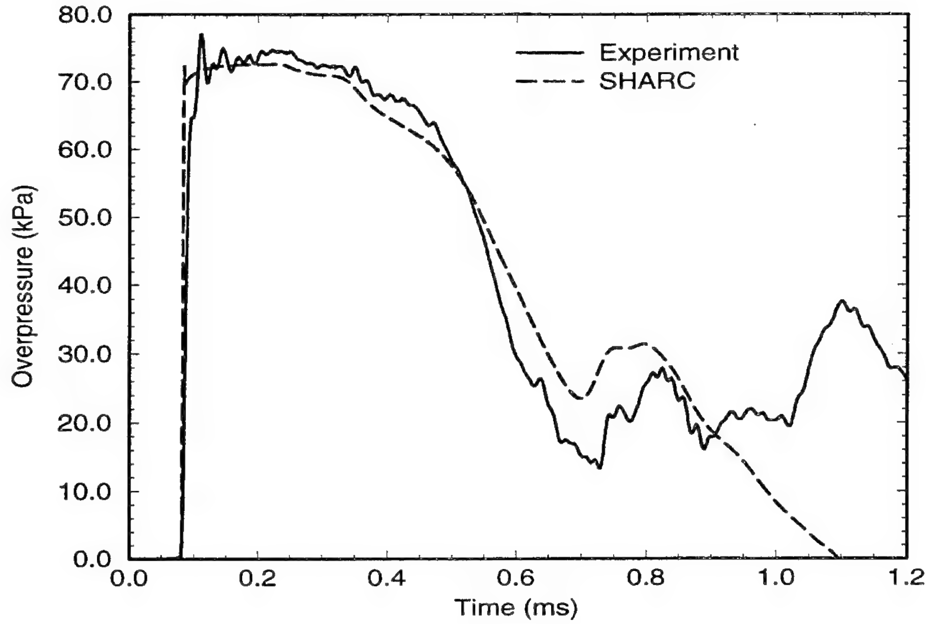

Figure 7. $M_s = 1.265$, Top Face, SHARC: First Order, 522x294 Grid

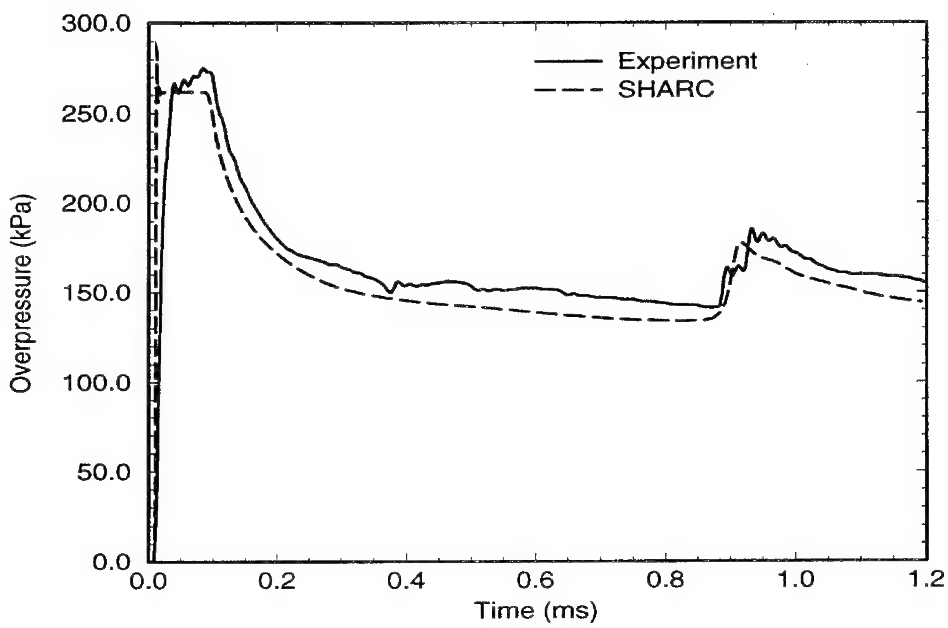

Figure 8. $M_s = 1.362$, Front Face, SHARC: First Order, 522x294 Grid

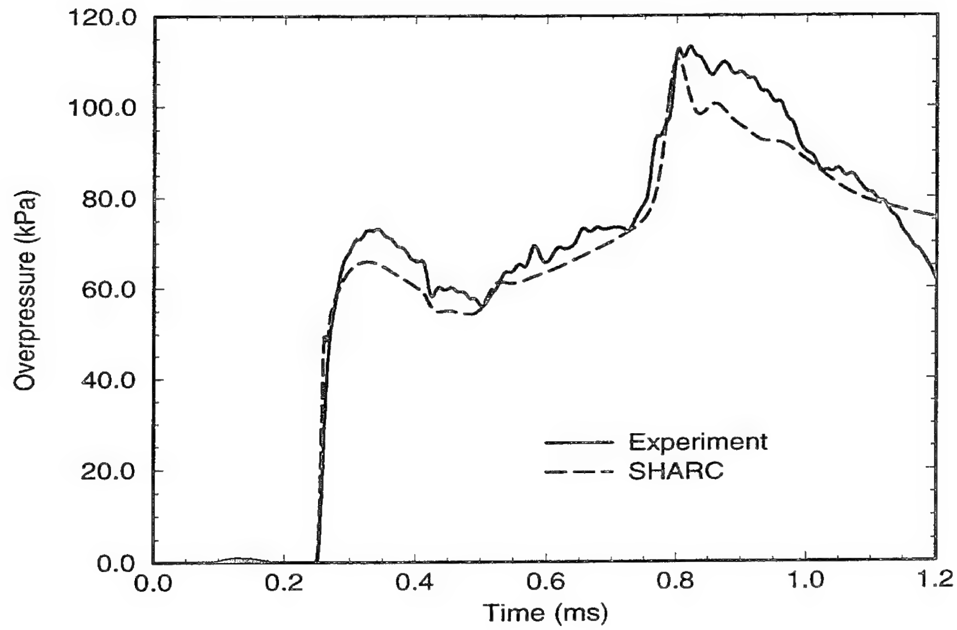

Figure 9. $M_s = 1.362$, Rear Face, SHARC: First Order, 522x294 Grid

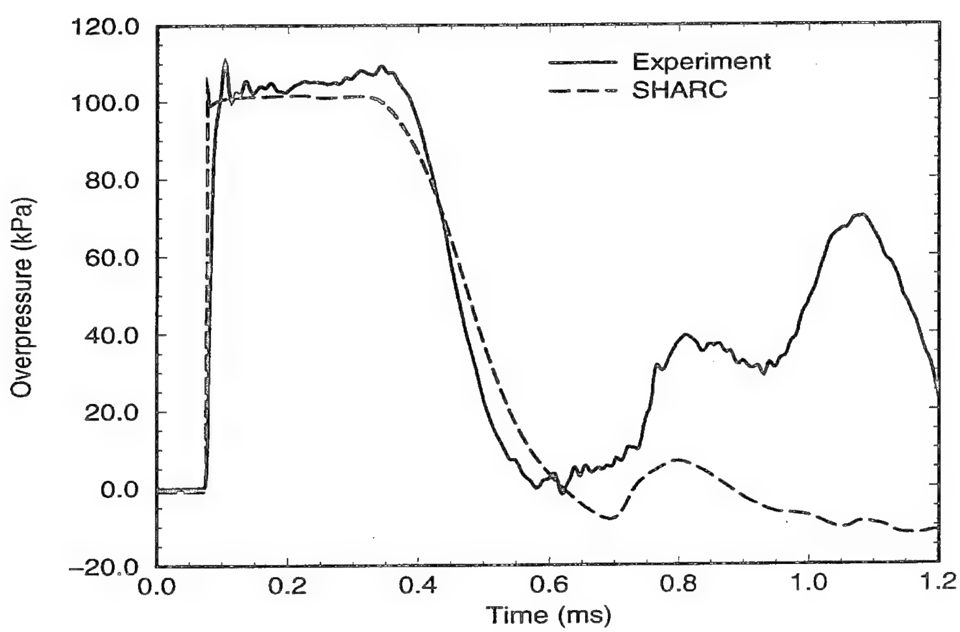

Figure 10. $M_s = 1.362$, Top Face, SHARC: First Order, 522x294 Grid

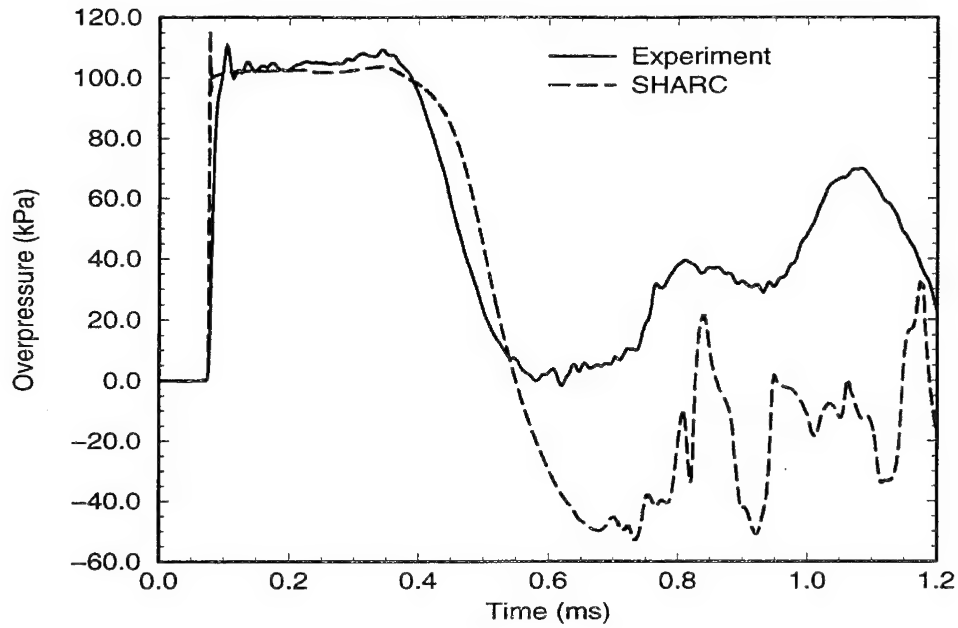

Figure 11. $M_s = 1.362$, Top Face, SHARC: Second Order, 522x294 Grid

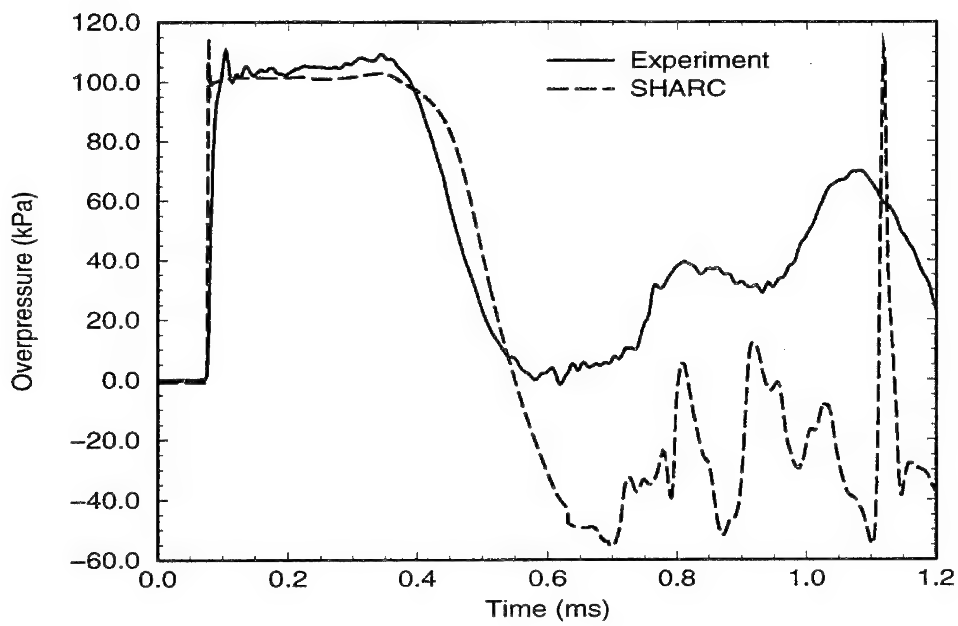

Figure 12. $M_s = 1.362$, Top Face, SHARC: Second Order, 522x652 Grid

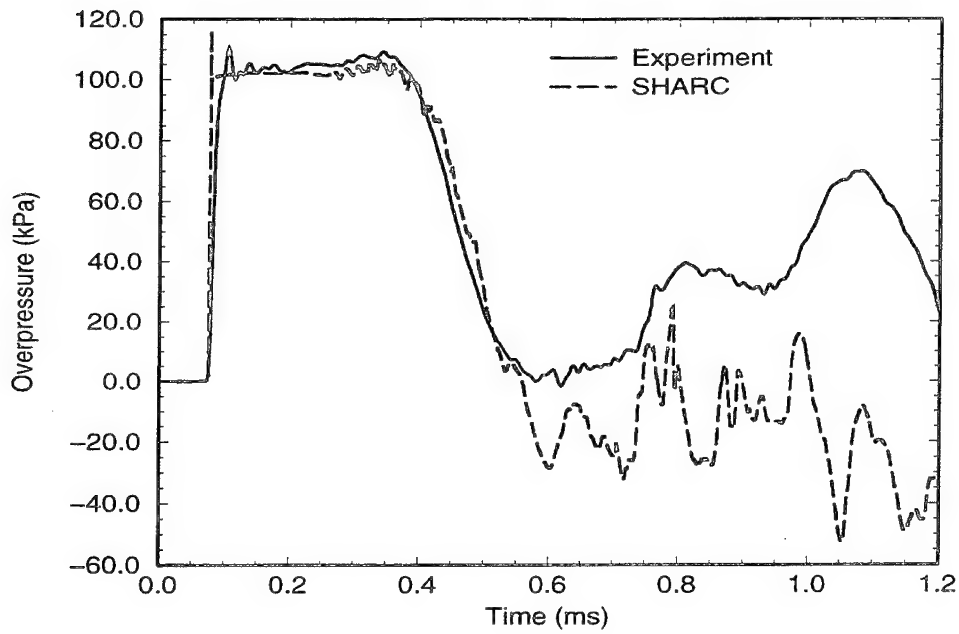

Figure 13. $M_s = 1.362$, Top Face, SHARC: Second Order, 958x1072 Grid

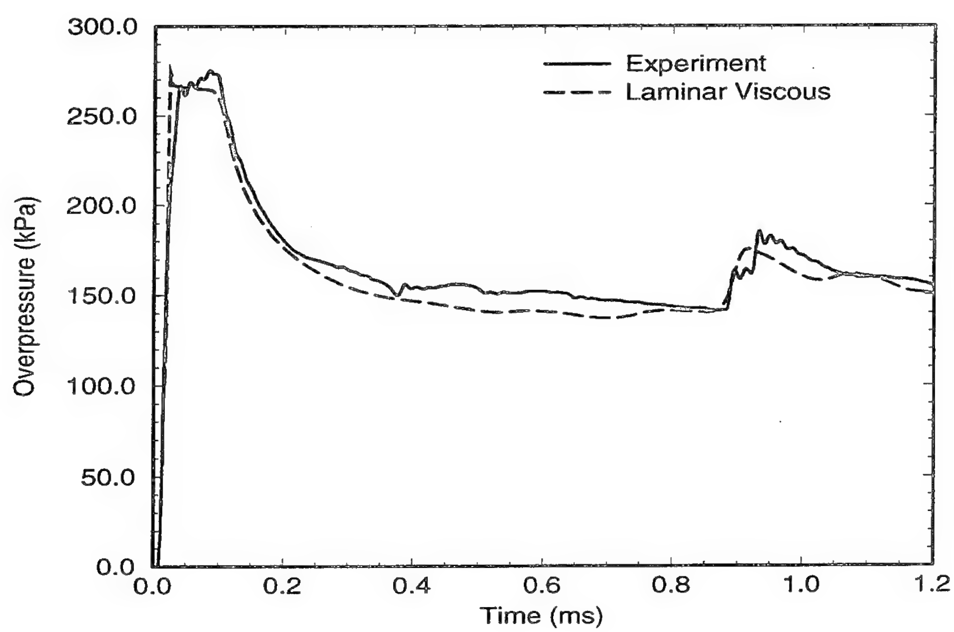

Figure 14. $M_s = 1.362$, Front Face, USA-RG2, Laminar-Viscous

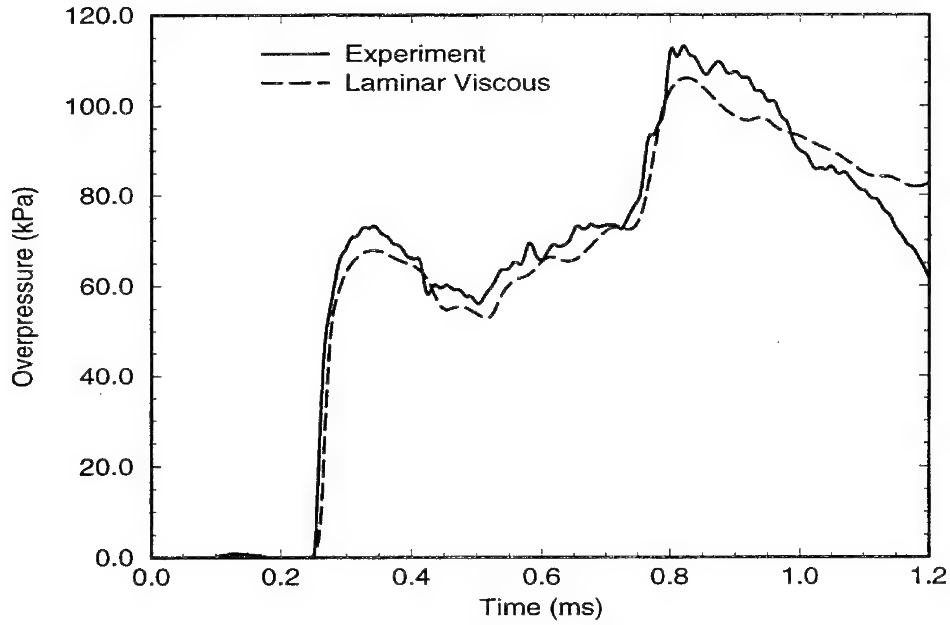

Figure 15. $M_s = 1.362$, Rear Face, USA-RG2, Laminar-Viscous

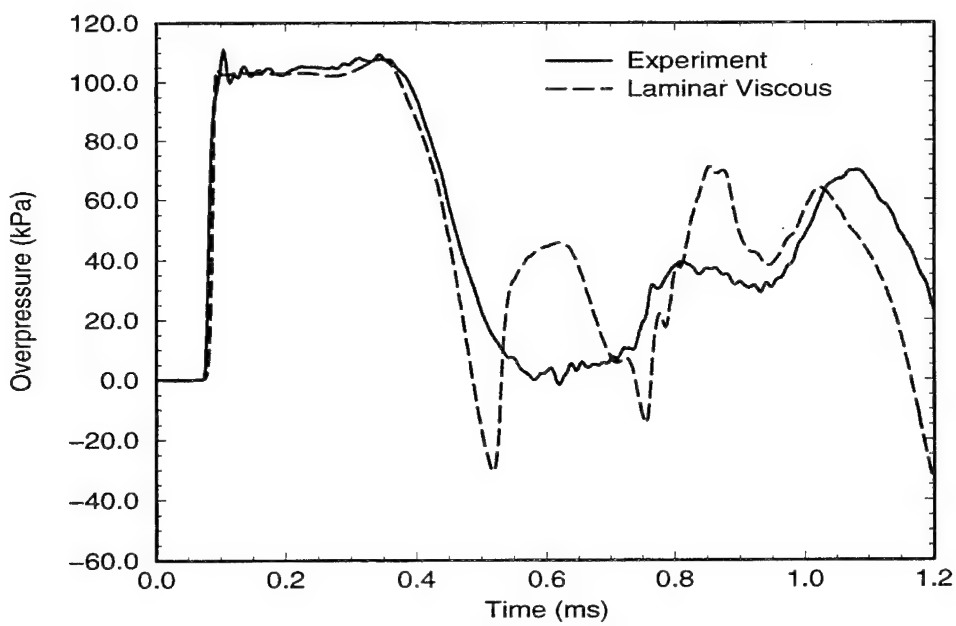

Figure 16. $M_s = 1.362$, Top Face, USA-RG2, Laminar-Viscous

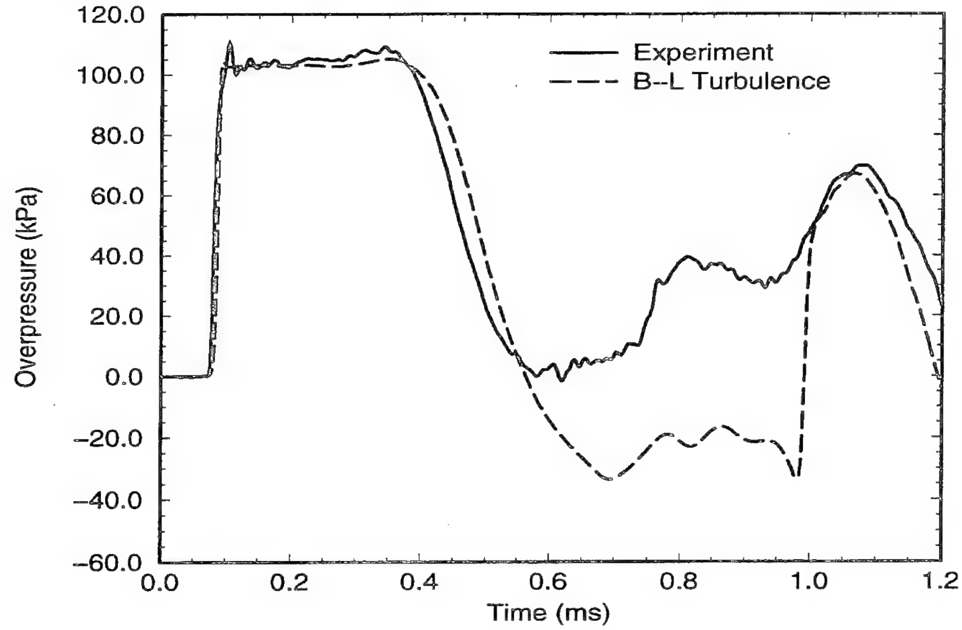

Figure 17. $M_s = 1.362$, Top Face, USA-RG2, B-L Turbulence

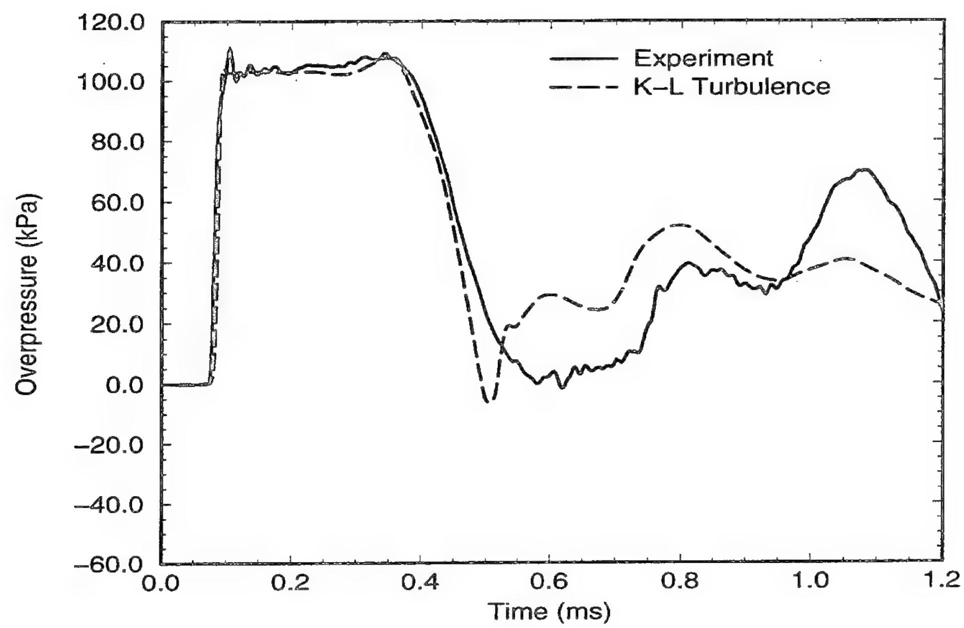

Figure 18. $M_s = 1.362$, Top Face, USA-RG2, k-L Turbulence

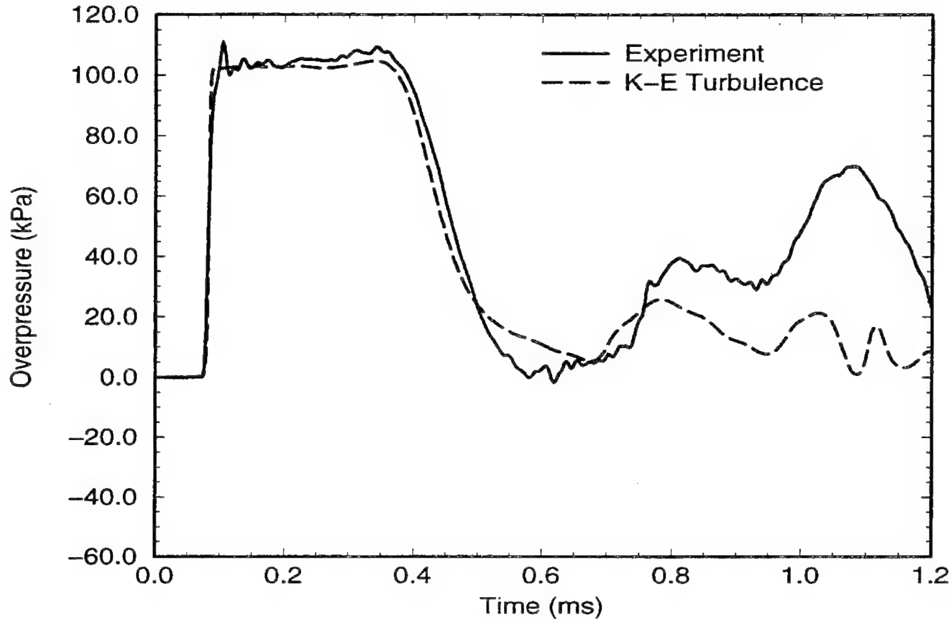

Figure 19. $M_s = 1.362$, Top Face, USA-RG2, k-ϵ Turbulence

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References

1. Tournemine, D. and P. Roulades. "Tube à Choc de Laboratorie Zephire - Présentation." Technical Report T-90-43. Centre d'Etudes de Gramat, France. June 1990.

2. Hikida, S., R. Bell, and C. Needham. "The SHARC Codes: Documentation and Sample Problems." S-Cubed Technical Report SSS-R-89-9878. September 1988.

3. Fry, M., R. Durret, G. Ganong, D. Matuska, M. Stucker, B. Chambers, C. Needham and C. Westmoreland. "The HULL Hydrodynamics Computer Code." U.S. Air Force Weapons Laboratory Technical Report 76-183, September 1977.

4. Barthel, J. "2-D Hydrocode Computations Using a $k - \epsilon$ Turbulence Model: Model Description and Test Calculations." S-Cubed Technical Report SSS-TR-85-7115. June 1985, (Footnotes added August 1988).

5. Chakravarthy, S., K. Szema, U. Goldberg, J. Gorski and S. Osher. "Application of a New Class of High Accuracy TVD Schemes to the Navier-Stokes Equations." AIAA Paper 85-0165. January 1985.

6. Opalka, K. "Numerical Simulation of the Flow in a 1:57-Scale Axisymmetric Model of a Large Blast Simulator." U.S. Army Research Laboratory Technical Report ARL-TR-111, Aberdeen Proving Ground, MD. April 1993.

7. Ramakrishnan, S. and U. Goldberg. "Versatility of an Algebraic Backflow Turbulence Model." AIAA Paper 90-1485. 1990

8. Goldberg, U. and S. Chakravarthy. "Separated Flow Predictions Using a Hybrid $k - L$/Backflow Model." AIAA Journal, Volume 28, Number 6. pp. 1005-1009. June 1990.

9. Goldberg, U. and D. Ota. "A $k - \epsilon$ Near-Wall Formulation for Separated Flows." AIAA Paper 90-1482. 1990.

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